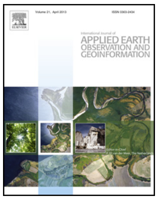
International Journal of Applied Earth Observation and Geoinformation 33 (2014) 280–289

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Assessment of reference evapotranspiration using remote sensing and forecasting tools under semi-arid conditions

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ARTICLE INFO

Article history:
Received 8 April 2014
Accepted 12 June 2014

Keywords:
Reference evapotranspiration
Remote sensing
MSG
ECMWF
Lysimeter
Advection

ABSTRACT

Reference evapotranspiration (ET_o) assessment at regional scale is a challenge to agricultural and hydrological research requiring the characterization of vast areas to obtain accurate meteorological variables. To account for this, a new approach considering a modified version of the Makkink equation and based on a combination of remotely sensed solar radiation (R_s) considering the MSG satellite, and numerical weather forecast of near surface air temperature (T_{2m}), was developed. The new approach is referred as Makkink-Advection equation (MAK-Adv).

Once R_s and T_{2m} were validated for the semiarid conditions registered in Southern Spain with very satisfactory results (RMSE = 1.6 MJ m^{-2} d^{-1} and 1.4 °C respectively, with linear regressions with slope = 0.99 and R^2 = 0.97), the MAK-Adv approach was calibrated and validated with ET_o measurements from a weighing lysimeter under near-reference conditions in Southern Spain. The new approach has provided accurate daily ET_o estimations compared with lysimeter data (RMSE = 0.50 mm d^{-1}, RE = 12.3% and MAE = 0.39 mm d^{-1}), and remains accurate during summer time (RMSE = 0.62 mm d^{-1} and RE = 9%), the critical period when accurate ET_o data are essential for a correct agricultural water management.

Once calibrated and validated, and thanks to the use of remotely sensed data, the MAK-Adv approach allowed the ET_o assessment at regional scale. For a semi-arid region located in southern Spain with an area of 87,300 km^2, a detailed spatial ET_o assessment was performed, determining ET_o values for the totality of the area with a resolution of about 9 km^2 allowing to evaluate the spatial and temporal variability at basin/region scale. This new approach gets over the serious limitations for a correct ET_o assessment when traditional methodologies are not able to provide these data for vast areas, even with the modern weather station networks. Thus, MAK-Adv approach is especially useful for those areas with missing or inaccurate meteorological in situ observations.

Introduction

Reference evapotranspiration (ET_o) is a key component of the hydrological cycle and base to estimate crop water requirements (Allen et al., 1998). ET_o is defined as the evapotranspiration, under the given meteorological conditions, of a reference grass crop with specific characteristics such as an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen et al., 1998).

The most accurate methodology for ET_o assessment is the use of weighing lysimeters (Malone et al., 2000). Weighing lysimeters have been long used to measure evapotranspiration (Wright, 1982). As such, lysimeters are the standard method to directly measure ET_o (Xu and Chen, 2005; López-Urrea et al., 2006) or crop ET (Yang et al., 2000; Lorite et al., 2012) and therefore the best source of observations for independent validation of ET_o estimates. However the available lysimeter data are very limited and alternative procedures such as Penman–Monteith approach (PM-FAO56) have been developed. Thus, PM-FAO56 has been compared with lysimeter measurements under semi-arid environments (Berengena and Gavilán, 2005; López-Urrea et al., 2006) obtaining very accurate ET_o estimations. This equation is, therefore, considered the standard procedure for ET_o estimation (Allen et al., 1998), leading to a satisfactory performance even under advective conditions (Berengena and Gavilán, 2005). However, the required input data (solar radiation, wind speed, temperature and relative humidity of the air) must be collected under the previously described reference conditions (Allen et al., 1998). This is often not possible or impractical, particularly in semi-arid regions where a

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http://dx.doi.org/10.1016/j.jag.2014.06.008
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network of such stations is difficult and costly to maintain, limiting the widespread use of this equation (Pereira and Pruitt, 2004). As a consequence, PM-FAO56 has often been substituted by approaches with lower input requirements such as Hargreaves or Makkink equations (Gavilán et al., 2006; De Bruin et al., 2010) using weather data from weather station networks.

In addition, weather stations networks are usually located close to irrigated areas (Gavilán et al., 2006), and then a correct weather characterization for non-irrigated areas and for hydrological purposes is even more difficult. Furthermore, the number of the weather stations is clearly limited, and vast areas are located far of well-managed weather stations (Voogt, 2006) avoiding a correct weather characterization. For example, Collins (2011) described the huge limitations depicted in Africa caused by low density of weather stations and usually unevenly distributed. An alternative for this limitation has been the use of spatial interpolation approaches (Alves et al., 2013), but several authors indicated the uncertainty in those datasets derived from interpolation methods (Ramirez-Villegas and Challinor, 2012). Thus, the development of new methodologies applied at regional scale and requiring lower cost observations is required, with a high impact on the availability and quality of ET_o estimations over many parts of the globe.

As a potential solution for the necessity of a new tool for ET_o assessment, the contribution of remote sensing must be considered. Remote sensing techniques have contributed in the improvement of water management at basin scale in the last years. The most advanced approaches have been focused on the determination of crop evapotranspiration (ET_c), using energy balance models (Galleguillos et al., 2011; Poças et al., 2013) or vegetation indexes (Ghilain et al., 2012). These approaches have provided relevant information for hydrological cycle analysis and agricultural water management, enabling the determination of crop water requirements (Santos et al., 2010), crop yield forecasting (De Wit and van Diepen, 2008), the analysis of the spatial and temporal variability of the vegetation (Stisen et al., 2008; Ghilain et al., 2012) or hydrological analyses (Bailly et al., 2011). For ET_o assessment, although recently De Bruin et al. (2010), Cammalleri and Ciraolo (2013) and Sepulcre-Canto et al. (2014) have demonstrated that geostationary satellite data can be used to determine ET_o values for vast areas, studies have been less numerous, being required further analyses related with new input data methodologies and regional calibration (Cammalleri and Ciraolo, 2013). Furthermore, despite the promising preliminary results concerning the feasibility of ET_o estimation derived from remotely sensed solar radiation from geostationary satellite MSG (De Bruin et al., 2010; Cristobal and Anderson, 2012), a calibration and validation of this empirical approach is still required, particularly under semi-arid conditions.

The main objective of the current study is to evaluate the use of an innovative approach using remotely sensed and ECMWF data for ET_o assessment at regional scale to get over the serious limitations of traditional methodologies for ET_o assessment in vast areas. Equally, an evaluation of the spatial and temporal variability at regional scale and the study of the main factors influencing the quality of the estimations are considered. To carry out these objectives, the introduced methodology considered weighing lysimeter and weather station data under semi-arid conditions in Southern Spain.

Materials and methods

EUMETSAT LSA SAF and ECMWF products

The EUMETSAT Satellite Applications Facility for Land Surface Analysis (LSA SAF) is part of the SAF network, a set of specialized development and processing centers serving the European Organization for the exploitation of meteorological satellites (EUMETSAT) (Trigo et al., 2011). The main objective of LSA SAF is the development of remote sensing applications relevant to land surface processes and biosphere applications, such as the case of ET_o (Trigo et al., 2011). The main input to ET_o satellite retrievals analyzed here is daily solar radiation at the surface. Within the LSA SAF this corresponds to the so-called daily down-welling surface shortwave radiation flux (DIDSSF) in the wavelength interval 0.3–4 μm (Geiger et al., 2008; Trigo et al., 2011). DIDSSF was determined from the accumulation of 30-min observations provided by the spinning enhanced visible and infrared imager (SEVIRI) radiometer, on board MSG (Schmetz et al., 2002) at a pixel resolution of 3 km at nadir (Trigo et al., 2011).

Air temperature at 2 m (T_{2m}) was obtained from the operational forecasts provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The initial 3-hourly T_{2m} forecasts at a resolution of about 25 km were linearly interpolated in time to hourly, and bi-linearly interpolated in space to the SEVIRI/MSG resolution (3 km at nadir). As ECMWF model surface orography and the SEVIRI elevation model showed differences in the pixel altitude caused by the different spatial resolution, the T_{2m} values underwent an adjustment to correct these altitude differences using a constant slope rate of 0.0067 °C m^{-1} (De Bruin et al., 2010). Thus, the T_{2m} values were reduced or increased at the indicated slope rate when the SEVIRI elevation was higher or lower than the ECMWF elevation, respectively. These adjusted T_{2m} values are considered for ET_o estimations by EUMETSAT LSA SAF (Trigo et al., 2010). A detailed full-description of ECMWF data is available in Persson (2011).

The EUMETSAT LSA SAF (Trigo et al., 2011) is planning to generate and distribute ET_o primarily based on solar radiation using MSG satellite measurements and ECMWF forecasts. In the context of the LSA SAF (De Bruin et al., 2010, 2012a; Trigo et al., 2011), such satellite based estimations make use of an empirical procedure based on Makkink equation, yielding ET_o for the whole field of view of the European geostationary satellite MSG. These results will be made available in near-real-time (http://landsaf.meteo.pt) at the MSG pixel resolution (3 km at nadir; Trigo et al., 2011), and cover an area encompassing Africa, most of Europe and part of South America.

Experiment setup for lysimeter and meteorological variables collection

A weighting lysimeter provided reference evapotranspiration data to carry out the calibration and validation process for MAK-Adv approach. It was installed in 1985 and is located in the center of a well-watered grass field with a size of 1.6 ha (Fig. 1), with regular agricultural practices in order to follow the FAO recommendations (Allen et al., 1998), being usually surrounded by fields cultivated with rainfed crops. These grass field characteristics and the weather conditions of the area generated a significant process of heat advection, with values of the ratio between reference evapotranspiration and net radiation (defined as the advection index) around 1.0–1.4 (Berengena and Gavilán, 2005), depicting advection for most of the sampled days (Gavilán and Berengena, 2007). These values indicate clear advection conditions for the grass field where the weighting lysimeter is installed.

The lysimeter facility, described in Berengena and Gavilán (2005), has provided accurate ET_o measurements for the last 20 years (Mantovani et al., 1995; Farahani et al., 2007; Gavilán et al., 2007), constituting a high valuable dataset very uncommon in the world. In order to ensure the quality of the collected data from this facility, its performance was checked once a year by placing known mass pieces on the lysimeter. Measurements were made increasing and decreasing the load on the platform by adding and removing pieces respectively (Gavilán and Berengena, 2007),

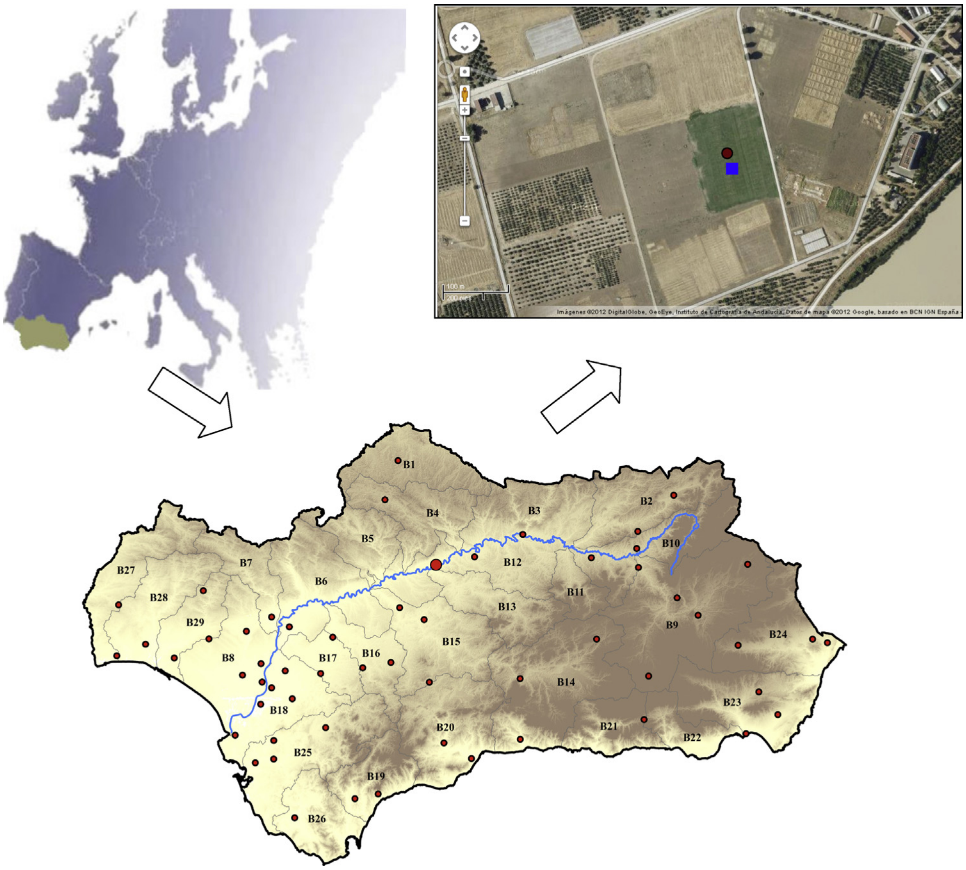

Fig. 1. Location of IFAPA experimental field in southern Spain (marked with a red circle) and picture showing the location of the weather station (red circle) and lysimeter (blue rectangle). In the map the weather stations included in RIA network, sub-basins considered in the study and the Guadalquivir River are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

obtaining correlations between added mass and scale reading very high with no significant differences. In addition, management and maintenance practices followed the recommendations provided by Allen and Fisher (1990) and Allen et al. (1991), and those days when irrigation or mowing occurred were discarded.

Lysimeter measurements were conducted for three years (2007–2009). After a detailed validation process, 270 days were considered including different weather conditions. Daily ET_o values depicted a clear seasonal trend, with the maximum ET_o values attained in mid-July with values around 7 mm d^{-1}, and minimum values around 1 mm d^{-1} in January.

The Agroclimatic Information Network of Andalusia (RIA; Gavilán et al., 2006) is currently composed of 100 automatic weather stations, but after to evaluate the data quality for the analyzed period, uniquely 56 weather stations were considered (Fig. 1). One of this is located close to the lysimeter facility described above centered on the reference experimental field and was used in the study (Fig. 1). This weather station is equipped with sensors to measure air temperature and relative humidity (HMP45C probe, Vaisala, Helsinki, Finland), solar radiation (pyranometer CM6B, Kipp&Zonen, Delft, Holland), wind speed and direction (wind monitor RM Young 05103, Traverse City, Mich.) and rainfall (tipping bucket rain gauge ARG 100). Mean semi-hourly and daily average values are recorded and validated for each meteorological variable. Different tests such as record structure data, range, step and persistence, internal consistency test and spatial consistency test according to Meek and Hatfield (1994) and Shafer et al. (2000) are considered.

Overall local weather conditions during the three-year period under study were quite similar, and coincide with average regional weather conditions at Southern Spain (Gavilán et al., 2006). Average maximum and minimum air temperatures were of around 24 °C and 10.5 °C, respectively, with a maximum and minimum relative humidity of 83% and 35%, respectively. Average wind speed was 1.6 m s^{-1} and daily solar radiation 18 MJ m^{-2} d^{-1}.

Reference ET equations

Penman–Monteith equation

The standardized Penman–Monteith (PM-FAO56) equation (Allen et al., 1998) is based on the Penman–Monteith equation (Monteith, 1965). For grass reference surface and for daily time step, this equation is expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273)) + 273U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is the reference evapotranspiration (mm d^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); T_{2m} is the mean daily air temperature at 2 m (°C); U_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa); Δ is the slope of saturated vapour–pressure curve (kPa °C^{-1}) and γ is the psychometric constant (kPa °C^{-1}).

Since measurements of ET_o over a grass reference crop (Allen et al., 1998) are often not available (De Bruin et al., 2010), several authors consider the estimations provided by PM-FAO56 as the benchmark for comparison with other equations and methodologies (Gavilán et al., 2006; Er-Raki et al., 2010; Espadafor et al., 2011; Cammalleri and Ciraolo, 2013), although reference conditions requirements (Allen et al., 1998) were not always fulfilled.

Advection-revised Makkink equation (MAK-Adv)

De Bruin (1987) and De Bruin and Lablans (1998) determined that under non-water stress conditions, ET_o (mm d^{-1}) could be accurately estimated using a simplified Makkink formula (Makkink, 1957) considering a parameter called c_{MAK}. This parameter ranges between 0.63 for Netherlands (Van Kraalingen and Stol, 1997) and 0.81 for the Jordan Valley (Jitan, 2005), depending on climate conditions. De Bruin (1987) and De Bruin et al. (2010) found that a c_{MAK} value corresponding to advection free conditions should be equal to 0.65, and Xu and Chen (2005) for a humid site in Germany determined a c_{MAK} value equal to 0.70. Cristea et al. (2013) defined c_{MAK} parameters for numerous locations at USA, ranging from 0.72 for Washington to 0.90 for Colorado, determining small model coefficient variability over a range of climates. For Southern Spain, c_{MAK} parameter was calculated for some representative weather stations located under different weather conditions in basins B8, B10, B12, B14, B18, B19 and B23 (Fig. 1). This parameter ranged from 0.77 for a weather station located within an irrigated area close to the sea in the basin B18, to 0.87 for an arid location at the east of the region (basin B23), depicting a significant homogeneity in c_{MAK} parameter.

Using the ET_o dataset gathered over the lysimeter site described in “Experiment setup for lysimeter and meteorological variables collection” a revised version of the Makkink equation to account for advective effects observed in the area (Gavilán and Berengena, 2007) was developed. Under semi-arid conditions advection of sensible heat on irrigated areas supplies a substantial amount of energy to the ET process, and then these advection conditions detected in the experimental field affected decisively to the calibration process carried out for the Makkink equation. For this reason the new equation was labeled as “advection-revised”, been the advection effects accounted throughout specific equation coefficients. In these, local weather variables such as wind speed, temperature and relative humidity are included. This new Makkink equation has been presented before in another form by De Bruin et al. (2012b; their equation 2 at air pressure $p = 100$ kPa).

The calibration of the procedure uses lysimeter ET_o data collected during 2008 (83 daily observations). For the calibration dataset, the RMSE of the MAK-Adv approach with respect to lysimeter ET_o values was 0.50 mm d^{-1}, corresponding to a relative error (RE) of 12.9% and an absolute mean error (MAE) of 0.37 mm d^{-1}. Consistently, the fit of the regression analysis presents very satisfactory results (slope = 0.95 and $R^2 = 0.96$). The result of these studies was the development of a new Makkink equation, denoted as *MAK-Adv*:

$$ET_o = \frac{1}{\lambda}[0.38 + 0.015(T_{2m} - 12)]R_s \qquad (2)$$

where R_s and T_{2m} were provided by LSA SAF from MSG satellite and ECMWF tool using the slope rate described in “EUMETSAT LSA SAF and ECMWF products”, respectively.

The validation was carried out using independent observations taken during 2007 and 2009. Results revealed very good statistics, with RMSE values of 0.46 and 0.54 mm d^{-1}, RE of 13.5% and 11.0%, and MAE of equal to 0.36 and 0.42 mm d^{-1} for 2007 and 2009, respectively. Regressions also presented a very good fit (slopes of 0.99 and 0.98; R^2 equal to 0.95 and 0.94).

With the analysis of the weather/climate conditions (wind speed, relative humidity, temperatures and c_{MAK} parameter) for the lysimeter location and at regional scale, the representativeness of the location where calibration/validation process was carried out is assured. This fact allows the use of MAK-Adv approach under different weather conditions with reliable outcomes.

Statistical analysis for model inter-comparison

Linear regressions used for model intercomparison were determined applying the least square method, setting the intercept to zero. Significance level for means of the analyzed approaches were determined using the least significant difference (LSD) all-pairwise comparison test based on *t*-test with a level of significance $\alpha = 0.05$. To determine the relationship between climatic variables and errors in the ET_o assessment, the coefficient of correlation was considered.

Results and discussion

Solar radiation and air temperature assessment using remote sensing and forecasting tools

Solar radiation (R_s) provided by LSA SAF for the study area closely followed a normal distribution, being the majority of the R_s values between 6200 and 6600 MJ m^{-2} year^{-1} (Fig. 2). R_s simulated values presented very good results when compared with the measurements obtained at the weather station (Fig. 3) located in the reference field (”Experiment setup for lysimeter and meteorological variables collection”). R_s values provided by LSA SAF slightly underestimated observations, with an averaged difference of 0.4 MJ m^{-2} d^{-1} (Table 1). The RMSE was 1.6 MJ m^{-2} d^{-1} corresponding to a relative error below 10%. The linear regression between the weather station and LSA SAF values generated a slope of 0.98 with $R^2 = 0.97$ (Fig. 3a). These results are overall more accurate than R_s estimates analyzed recently by other authors: Bois et al. (2008) found underestimations in France with relative RMSE ranging from 14% to 20%, De Bruin et al. (2010) in Jordan Valley obtained a linear regression slope equals to 0.92 and $R^2 = 0.97$, Journée and Bertrand (2010) in Belgium determined RMSE equals to 104 W m^{-2} (about 9 MJ m^{-2} d^{-1}), Roerink et al. (2012) also determined accurate and unbiased errors with standard deviations between 30 and 51 W m^{-2} (about 2.5–4.5 MJ m^{-2} d^{-1}),

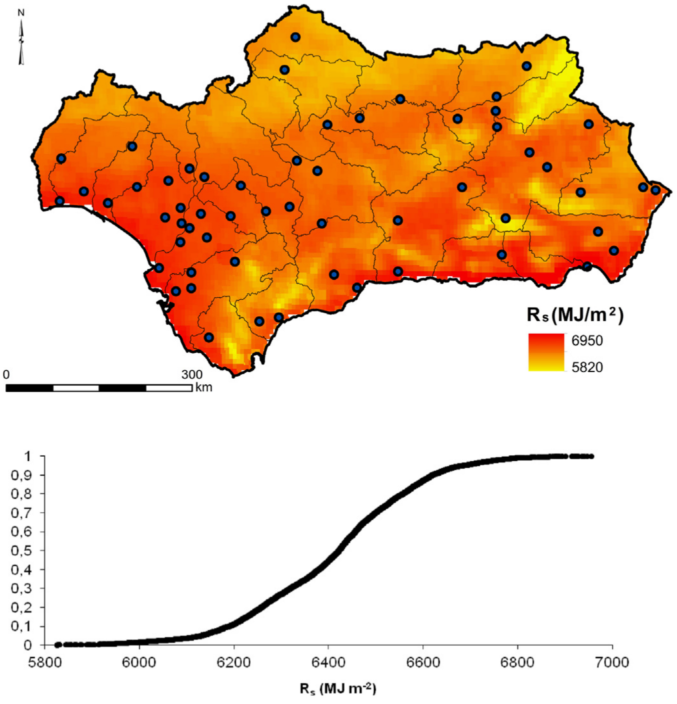

Fig. 2. Annual solar radiation (R_s) assessment for 2007 obtained with LSA SAF tool using the MSG satellite for the region of Andalusia, Southern Spain. Below, curve of cumulative frequency of the R_s values obtained from LSA SAF tool.

Table 1
Average R_s (MJ m^{-2} d^{-1}) and T (°C) values, errors and correlations obtained by LSA SAF and ECMWF for the whole analyzed period and by season.

Radiation	Avg. RIA (MJ m^{-2} d^{-1})	Avg. LSA (MJ m^{-2} d^{-1})	RMSE (MJ m^{-2} d^{-1})	RE (%)	MAE (MJ m^{-2} d^{-1})	Slope	R^2
Year	17.34	16.94	1.56	9.02	1.16	0.98	0.97
Winter	10.87	10.17	1.25	11.48	1.01	0.93	0.97
Spring	23.51	22.81	2.14	9.10	1.68	0.97	0.90
Summer	26.14	26.22	1.67	6.39	1.15	1.00	0.88
Fall	10.88	10.69	1.01	9.25	0.81	0.97	0.96

Temperature	Avg. RIA (°C)	Avg. LSA (°C)	RMSE (°C)	MAE (°C)	Slope	R^2
Year	17.12	16.80	1.36	1.09	0.99	0.97
Winter	10.41	9.75	1.36	1.10	0.93	0.85
Spring	17.73	16.81	1.40	1.14	0.95	0.95
Summer	26.78	26.86	1.10	0.85	1.00	0.85
Fall	13.72	13.99	1.55	1.26	1.02	0.85

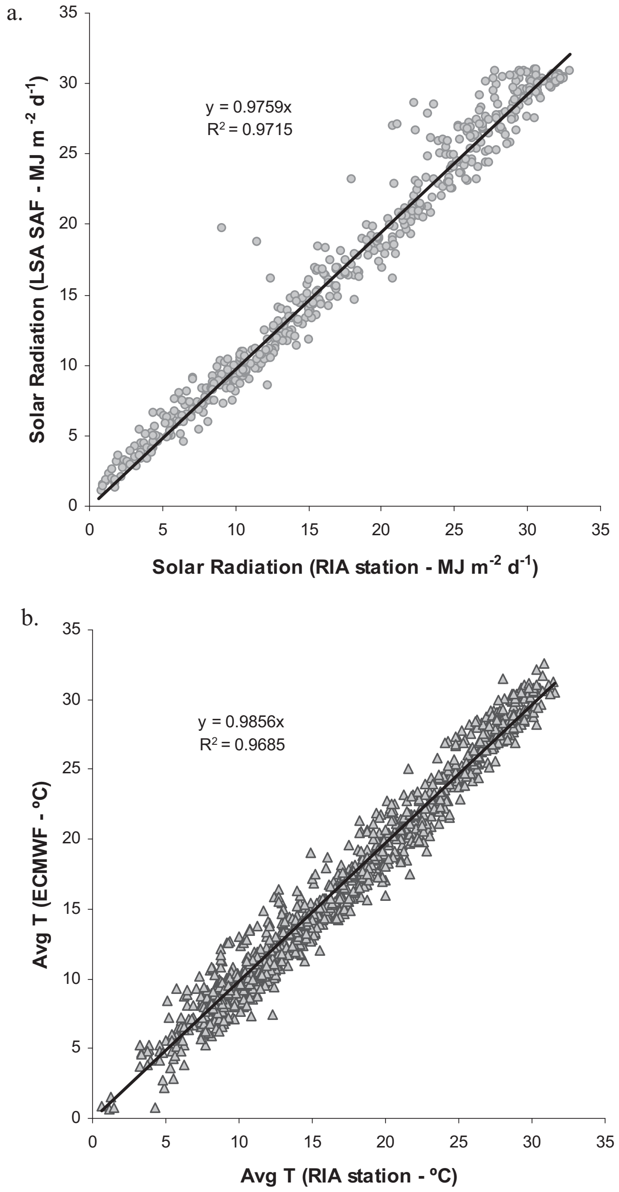

Fig. 3. (a) Comparison of solar radiation (MJ m^{-2} d^{-1}) provided by the weather station described in Experiment setup for lysimeter and meteorological variables collection, and LSA SAF; and (b) comparison of T (°C) provided by the weather station and ECMWF.

and Cristobal and Anderson (2012) in a Mediterranean area with lower aridity conditions than Andalusia obtained RMSD of 1.6 and 2.3 MJ m^{-2} d^{-1} for flat and hilly terrain, respectively.

ECMWF provided good average temperature values compared with measurements at the weather station. Average T_{2m} from ECMWF was 16.8 °C while that measured by the weather station was 17.1 °C, generating a very small underestimation (RMSE was 1.4 °C, Table 1). The regression between average T_{2m} values provided by ECMWF and the weather station generated a slope of 0.99 with $R^2 = 0.97$ (Fig. 3b). De Bruin et al. (2010) reported underestimations of ECMWF temperature uniquely in regions with high elevation, which agrees with the results obtained in this study (the experimental reference field is located at 117 m).

The performance of R_s and T_{2m} estimations provided by LSA SAF and ECMWF, respectively, was specially accurate during summer time, when clear sky dominates, presenting regression slopes of 1.0 and absolute errors of 1.15 MJ m^{-2} d^{-1} and 0.85 °C, for R_s and T_{2m}, respectively (Table 1). These results are consistent with the studies performed by the LSA SAF (Geiger et al., 2008; Trigo et al., 2011) and Cristobal and Anderson (2012) showing that the errors in the estimation of solar radiation are higher under cloudy conditions.

MAK-Adv approach compared with lysimeter measurements and ET_o equations

The results obtained for different ET_o approaches are shown in Table 2, considering as reference ET_o values those measured by the lysimeter. Daily ET_o lysimeter measurements and PM-FAO56 ET_o estimates are equal to 4.1 mm d^{-1} (Table 2), no detecting statistically significant differences between both methods. R^2 was 0.98 with slope equal to 0.98 (Fig. 4a).

Makkink (MAK) approach using LSA SAF and ECMWF data provided statistically significant lower ET_o values (3.56 mm d^{-1}) compared to ET_o measured by the lysimeter. RMSE was around 1.0 mm d^{-1} and MAE was 0.7 mm d^{-1} (Table 2). R^2 was 0.92 but the slopes are clearly below one (0.83). These low ET_o values agree with previous studies that confirmed ET_o underestimations using the Makkink equation under semi-arid conditions (Allen et al., 1998; Temesgen et al., 2005) due to the omission of the aerodynamic component in ET_o computation. Finally, Cammalleri and Ciraolo (2013) also determined underestimations with the Makkink approach, especially in sites with a strong wind, with average underestimations of around 4%.

Finally, compared with lysimeter measurements, MAK-Adv approach has given excellent results. The average ET_o value was 4.0 mm d^{-1} (1.5% lower with respect to lysimeter measurements) with differences no-statistically significant, RMSE equal to 0.50 mm d^{-1}, RE = 12.3% and MAE = 0.39 mm d^{-1} (Table 2). The slope of the regression was 0.97 and R^2 equals to 0.96 (Fig. 4a). These errors produced by the MAK-Adv approach were below the

Table 2
Average ET_o values, errors and correlations obtained with various ET_o approaches including ET_o values measured by lysimeter for 2007–2009 period.

	ET_o LYS	ET_o PM-FAO56	ET_o MAK	ET_o MAK-Adv	ET_o MAK-Adv + RIA
Avg. daily ET_o (mm d^{-1})	4.06ab	4.06a	3.56c	4.00a	4.14b
RMSE (mm d^{-1})	–	0.36	0.93	0.50	0.50
RE (%)	–	8.77	22.97	12.32	12.36
MAE (mm d^{-1})	–	0.28	0.69	0.39	0.39
Slope	–	0.98	0.83	0.97	0.99
R^2	–	0.98	0.92	0.96	0.95

In avg. daily ET_o, equal letters mean no statistically significant differences ($p < 0.05$).

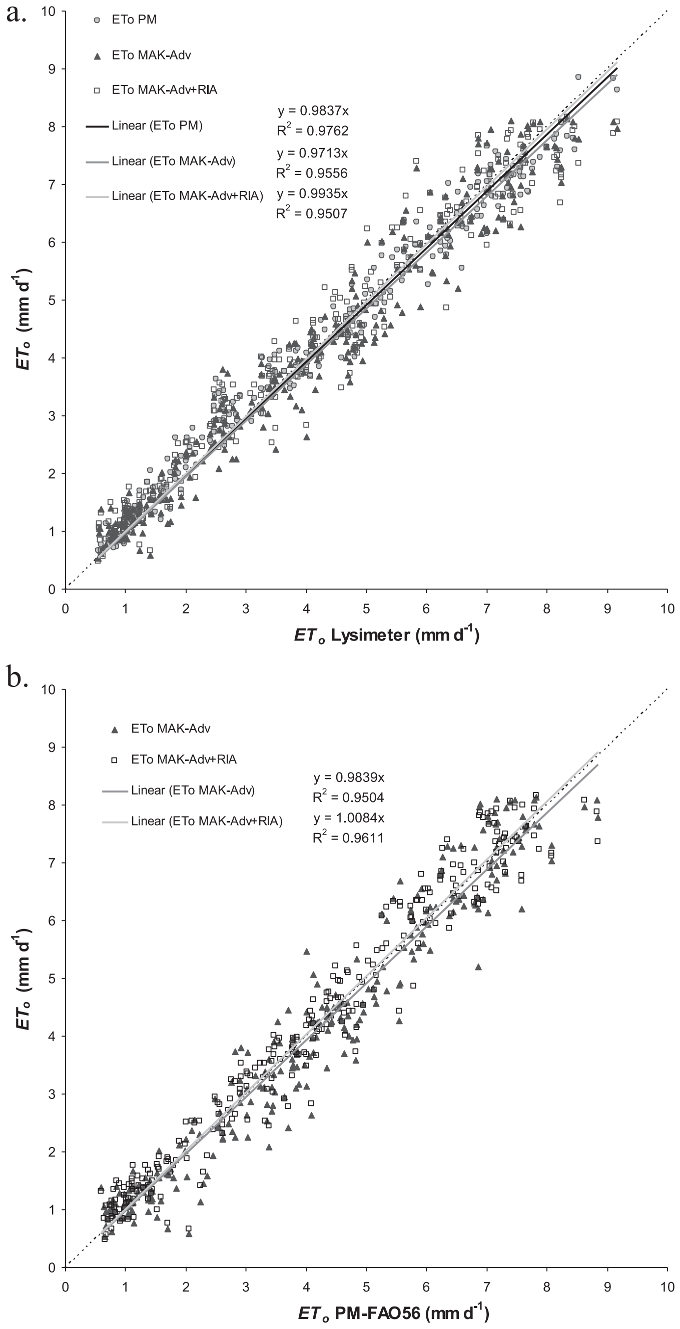

Fig. 4. (a) Comparison of different approaches for ET_o assessment (PM-FAO56, MAK-Adv and MAK-Adv + RIA) with ET_o measurements by lysimeter and (b) with PM-FAO56 approach.

instrumental errors. The comparison between MAK-Adv approach and PM-FAO56 values also presented high correlation (slope is equal to 0.98 and $R^2 = 0.95$; Fig. 4b) and non-statistically significant differences (Table 2). Thus, the use of PM-FAO56 as a reference gave a similar performance to that when using lysimeter data, and could be considered as a reference when spatial analyses are carried out, where lysimeter data are obviously not available.

Error analysis and climatic correlations

In order to determine the importance of a correct calibration of Makkink equation and its impact on the quality of the ET_o estimations, several c_{MAK} coefficients previously proposed around the world (Jitan, 2005; Xu and Chen, 2005; De Bruin et al., 2010; Cristea et al., 2013) were considered. For lysimeter location, the best figures were obtained with c_{MAK} equal to 0.81, value previously determined by Jitan (2005) at Jordan Valley, with RMSE equal to 0.58 mm d^{-1}. However when c_{MAK} was equal to 0.65 or 1.0 the errors in the ET_o estimation increased until RMSE = 0.95 and 1.3 mm d^{-1}, respectively. MAK-Adv approach with local calibration provided slightly better performance than using fixed non-locally calibrated c_{MAK} values (RMSE = 0.57 vs 0.58 mm d^{-1}, respectively), although in both cases the results were very satisfactory. Under different climate conditions at Southern Spain, considering the previous weather stations distributed throughout Andalusia, similar results were determined: c_{MAK} values around 0.81 provided the best figures compared with PM-FAO56 approach (RMSE = 0.61 mm d^{-1}), but were worse than using the proposed local calibration (RMSE = 0.59 mm d^{-1}). Equally, when c_{MAK} moved away from 0.81 results were worse: RMSE values were 0.78 and 1.21 mm d^{-1} when c_{MAK} was changed to 0.65 and 1.0 respectively. This analysis demonstrates the high impact of the calibration on the ET_o estimates with the Makkink equation, being required at least a regional calibration of the procedure to be applied to vast areas.

To determine the source of the errors in the proposed approach, the results obtained with MAK-Adv approach using SEVIRI-MSG/ECMWF data were compared with the MAK-Adv approach results using input data from the weather station considered in “Experiment setup for lysimeter and meteorological variables collection” (named MAK-Adv + RIA approach). The differences of MAK-Adv + RIA results with the lysimeter measurements were similar to those obtained with MAK-Adv, being both means statistically equal to the lysimeter data (Table 2), with a small improvement in the slope of the regression (Fig. 4a). This fact indicates that the small differences in the ET_o calculation were mainly caused by limitations in the approach, and not by the quality of the remotely sensed input data, since the errors caused by the inputs triggered negligible impacts on the ET_o assessment.

The performance of the MAK-Adv approach, as for the PM-FAO56 approach, varied throughout the year. The smallest differences with respect to measured ET_o by the lysimeter were found in summer (RE = 9.1%; Table 3), while the maximum errors were detected in winter and autumn (RE equals to 18.8% and 17.3% respectively). Similarly, the signal (under or overestimation) also depended on the season. While in summer and spring

Table 3
Seasonal comparison of different ET_o approaches (PM-FAO56, Makkink, Makkink-Adv and Makkink-Adv + RIA) with lysimeter measurements.

	ET_o LYS	ET_o PM-FAO56	ET_o MAK	ET_o MAK-Adv	ET_o MAK-Adv + RIA
Summer					
Avg. (mm d^{-1})	6.82	6.66	5.45	6.73	6.67
RMSE (mm d^{-1})		0.43	1.52	0.62	0.66
RE (%)		6.34	22.24	9.10	9.74
MAE (mm d^{-1})		0.37	1.38	0.52	0.52
Slope		0.97	0.79	0.98	0.97
R^2		0.90	0.72	0.75	0.72
Fall					
Avg. (mm d^{-1})	2.21	2.29	2.08	2.22	2.31
RMSE (mm d^{-1})		0.30	0.46	0.38	0.36
RE (%)		13.52	21.02	17.33	16.53
MAE (mm d^{-1})		0.22	0.34	0.27	0.29
Slope		1.02	0.89	0.99	1.02
R^2		0.95	0.86	0.91	0.92
Winter					
Avg. (mm d^{-1})	1.66	1.83	1.87	1.81	1.97
RMSE (mm d^{-1})		0.31	0.34	0.31	0.40
RE (%)		18.66	20.59	18.78	24.02
MAE (mm d^{-1})		0.22	0.28	0.24	0.33
Slope		1.10	1.07	1.06	1.15
R^2		0.94	0.85	0.89	0.92
Spring					
Avg. (mm d^{-1})	4.84	4.82	4.27	4.58	4.90
RMSE (mm d^{-1})		0.35	0.82	0.57	0.49
RE (%)		7.29	16.94	11.80	10.16
MAE (mm d^{-1})		0.28	0.66	0.46	0.39
Slope		0.99	0.87	0.94	1.01
R^2		0.91	0.77	0.85	0.86

small underestimations were detected (slopes equal to 0.98 and 0.94 respectively), during winter overestimations were found (overestimation by around 9% and slope = 1.06; Table 3). A different calibration for winter/autumn and spring/summer conditions might improve the MAK-Adv approach, but this potential improvement is very limited due to the excellent results shown by the model in the current version. The extra complexity of such approach is unlikely to pay-off.

A correlation analysis was carried out to determine relationships between the differences in the ET_o estimation of MAK-Adv approach with respect to lysimeter measurements, and some climate variables such as temperature or relative humidity. The differences were statistically significant ($p < 0.01$) negatively correlated with T_{2m} and R_s (coefficient of correlation equal to −0.32 and −0.39 respectively) and positively with relative humidity (0.34), showing that the errors were larger in days with low ET_o (−0.37). The results of these analyses confirm that the summer season, when higher R_s, T_{2m} and ET_o values occur more frequently, is the period with a better MAK-Adv performance. However, during the winter-autumn season, the ET_o assessment with the MAK-Adv approach displayed a greater uncertainty. These results fully agree with other analyses carried out under a Mediterranean climate by Bois et al. (2008) and Cristobal and Anderson (2013), with the best performance for ET_o assessment being seen during the summer season.

Spatial variability of ET_o using MAK-Adv approach

In order to extent the proposed approach at regional scale, ET_o estimations provided by MAK-Adv approach were compared with PM-FAO56 approach for seven representative locations (see “Advection-revised Makkink equation (MAK-Adv)”). For these locations, comparing the results provided by both approaches, average relative root mean square difference (rRMSD) was 15.9%, very similar to the value obtained in the experimental field where lysimeter is installed (15.5%). This performance was not equal for the whole region, with excellent figures for the Guadalquivir Valley and western areas (rRMSD = 12.7%) and slightly worse results for the eastern and arid areas (rRMSD = 20.2%). When c_{MAK} was around or higher than 0.85 the ET_o estimation with MAK-Adv approach was slightly underestimated, although the results were satisfactory. These results indicate that at least a regional calibration of the MAK-Adv approach is required, especially under extreme arid conditions.

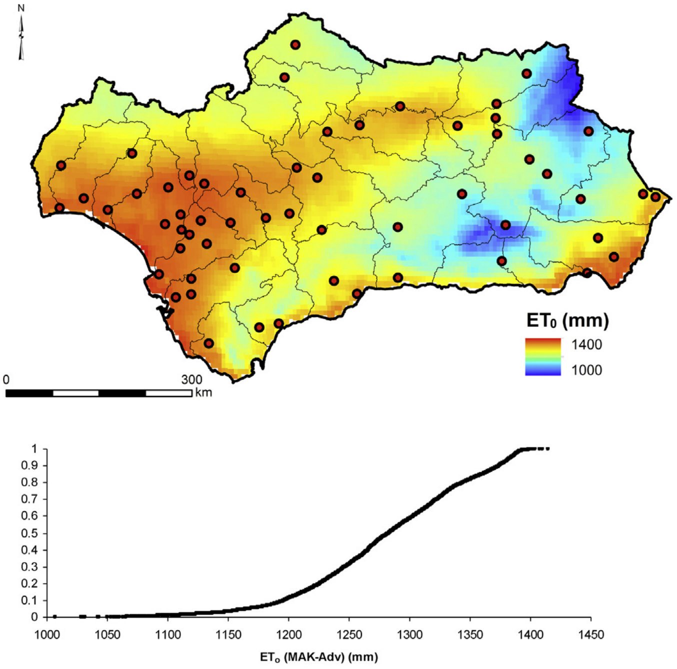

Fig. 5. Annual ET_o assessment for 2007 obtained with MAK-Adv approach for the region of Andalusia, Southern Spain. Below, curve of cumulative frequency of the ET_o values obtained with MAK-Adv approach.

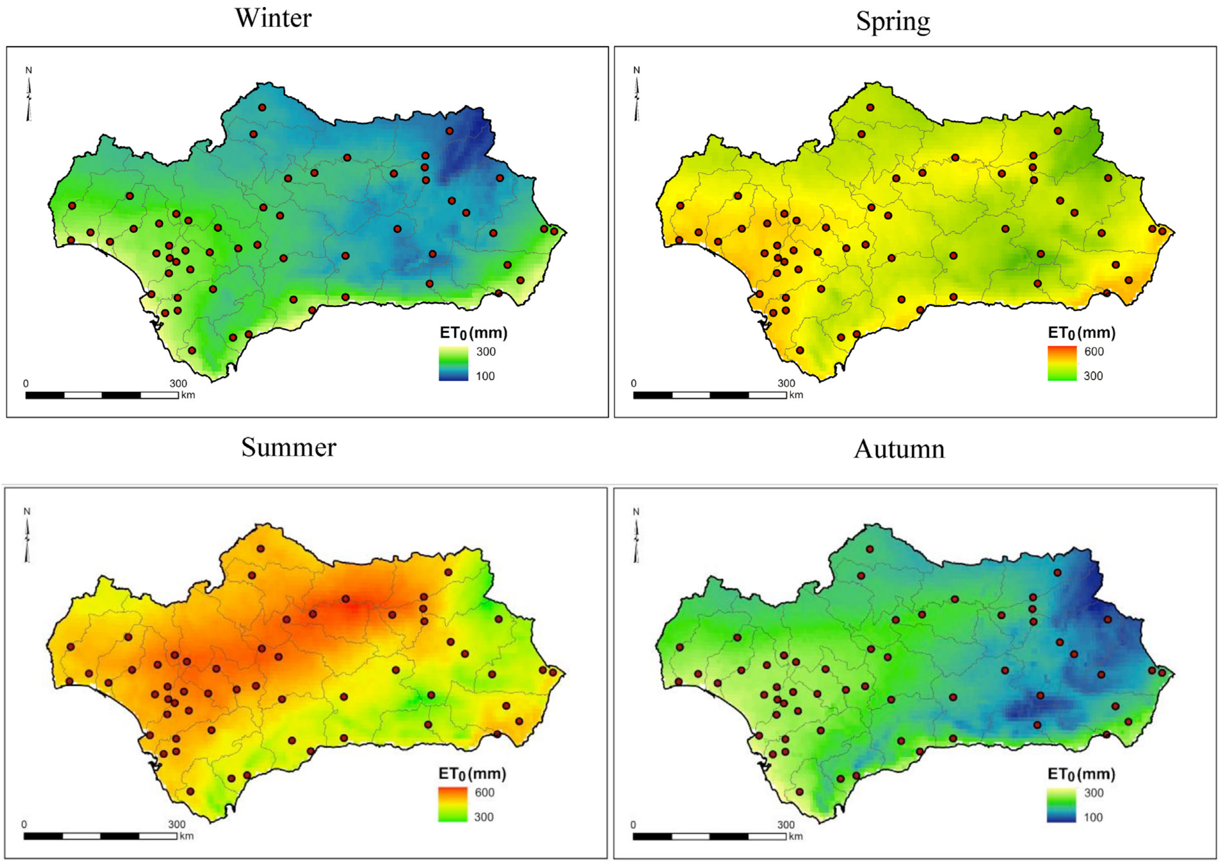

Fig. 6. Seasonal ET_o assessment for 2007 obtained with MAK-Adv approach for the region of Andalusia, Southern Spain. Different range of values for autumn and winter (100–300 mm) and for spring and summer (300–600 mm) were selected in order to improve the visualization of the results.

Table 4
Analysis at sub-basin scale (see Fig. 1) indicating number of RIA weather stations, average, minimum, maximum and average range of ET_o variation provided by MAK-Adv, and relative root mean square difference (rRMSD) between ET_o estimated by the weather stations from RIA and the ET_o estimated by MAK-Adv.

Code	Area (km^2)	RIA #Stations	MAK-Adv Avg. (mm)	MAK-Adv Min (mm)	MAK-Adv Max (mm)	Range Avg. (%)	rRMSD (%)
B1	2743	1	1253.1	1194.1	1281.7	3.5	2.8
B2	3435	2	1226.9	1063.3	1346.0	11.5	11.8
B3	3306	0	1292.9	1228.3	1351.1	4.8	
B4	2780	1	1278.2	1230.8	1323.2	3.6	6.7
B5	1917	0	1283.8	1261.1	1323.7	2.4	
B6	4077	1	1334.2	1277.9	1395.8	4.4	7.6
B7	1749	1	1319.2	1253.0	1396.7	5.4	5.6
B8	3646	5	1381.3	1323.3	1414.3	3.3	1.1
B9	7078	5	1194.9	1070.2	1264.6	8.1	13.1
B10	3309	2	1195.3	1029.0	1339.9	13.0	20.4
B11	1115	0	1265.9	1204.3	1345.2	5.6	
B12	3431	3	1323.4	1260.4	1354.4	3.5	3.2
B13	2429	0	1286.9	1233.1	1331.8	3.8	
B14	5920	3	1221.9	1112.2	1301.6	7.8	12.6
B15	3547	3	1311.6	1215.8	1363.9	5.6	4.6
B16	1792	2	1340.3	1286.2	1376.6	3.4	8.7
B17	1388	2	1365.2	1319.5	1395.8	2.8	12.0
B18	2697	4	1376.0	1319.5	1403.6	3.1	3.9
B19	2101	2	1272.5	1190.9	1315.9	4.9	2.9
B20	4006	2	1264.7	1196.6	1338.6	5.6	10.0
B21	2022	1	1211.8	1140.1	1289.1	6.1	3.7
B22	1479	0	1263.6	1161.5	1360.7	7.9	
B23	3890	3	1303.5	1151.9	1390.8	9.2	5.0
B24	3659	3	1242.7	1148.8	1338.4	7.6	8.2
B25	4176	4	1340.9	1232.5	1403.6	6.4	3.0
B26	2296	1	1287.6	1175.3	1375.5	7.8	8.6
B27	2870	1	1306.0	1246.6	1387.0	5.4	2.9
B28	2934	2	1346.8	1280.3	1389.9	4.1	5.5
B29	1810	2	1364.8	1307.1	1389.7	3.0	3.3

Once the calibration/validation process is made, and thanks to the use of remote sensing and forecast tools, the MAK-Adv approach is able to carry out spatial analyses of ET_o under semi-arid conditions for vast areas. A region located in Southern Spain (Fig. 1) during 2007 has been selected for the demonstration of the introduced approach (Figs. 5 and 6 and Table 4).

The MAK-Adv approach allows the estimation of daily ET_o maps with a spatial resolution of around 9 km^2, which can then be used to get yearly (Fig. 5) and seasonal ET_o maps (Fig. 6), determining the spatial and temporal variability of ET_o values. The annual ET_o for 2007 ranged between 1000 and 1400 mm, being the majority of ET_o values between 1200 and 1350 mm (Fig. 5), and reveals a clear spatial pattern, with the highest values located in the Mid-Lower section of Guadalquivir River Basin (GRB), coastal areas and arid zones in the East of the region, with maximum ET_o of the order of 1400 mm. The lowest ET_o values were found in mountainous areas located to the East of the region (ET_o ~1000 mm). Also a clear spatial pattern of ET_o depending on season can be seen in Fig. 6. For summer time, the maximum ET_o values were found in the GRB, particularly in the Mid-Upper section (maximum ET_o was ~600 mm). The lowest ET_o values were detected in the mountainous areas to the East, with values around 450 mm. Coastal areas had moderate ET_o values mitigated by the sea effect on temperatures. In autumn and winter periods the highest ET_o values were found in the coastal areas (maximum values close to 200 mm) and in the lowest section of GRB (Fig. 6). Minimum values were found in mountainous areas in the East (~100 mm). Finally, for spring maximum ET_o values were detected in the lowest section of GRB, coastal areas and arid zones in the East (~475 mm), while the minimum values were found in mountainous areas (~350 mm).

Variability in ET_o at sub-basin scale and for the whole region was high. Ranges of variation are showed in Table 4. At sub-basin scale, some sub-basins showed large variability (e.g. B10 ranged from about 1029–1340 mm). Spatial variability in ET_o was higher during winter and autumn (CV = 10.3 and 10.0% respectively) compared with spring and summer (5.3 and 6.1% respectively). Such high ET_o spatial variability suggests that the uncertainty in ET_o estimations in the absence of a near-by weather station is high. The use of the MAK-Adv approach, thanks to the use of remote sensed data, reduces significantly that uncertainty, since the satellite data is capable of capturing the spatial and temporal variability of solar irradiance at the surface, the main source of energy for ET_o (Fig. 6).

Errors associated with the limited number of stations were analyzed using the yearly and seasonal rRMSD determined comparing the ET_o values provided by the RIA with the provided by MAK-Adv at sub-basin scale (Table 4). Yearly rRMSD at sub-basin scale ranges from 1.1 to 20.4%. Seasonally, spring and summer seasons showed small rRMSD values (7.3 and 5.4%, respectively), with higher values for winter and autumn (20.1 and 17.9%, respectively). This implies that the use of ET_o values from individual weather stations for vast areas must be considered with caution, since high discrepancies generally occur when ET_o presents high spatial range and/or low number of stations within the basin (and therefore low representativeness of station-based estimates), are available.

Conclusions

The use of remote sensing techniques (LSA SAF) and forecast tools (ECMWF) integrated in the advection-revised Makkink equation (MAK-Adv approach) has given very satisfactory results in ET_o assessment under semi-arid conditions in Southern Spain, providing an excellent tool for spatially distributed ET_o assessment.

Thus, the new MAK-Adv approach improved the estimations (RMSE = 0.5 mm d^{-1}; RE = 12.3%; Table 2) compared with simpler methods as MAK approach, providing similar ET_o estimations to the results provided by other more complex methodologies such as lysimetry or PM-FAO56 (Fig. 4), but extending the ET_o assessment at regional scale. The results for summertime, the key season for agriculture water management, were particularly remarkable, with very accurate results (RMSE = 0.62 mm d^{-1}; RE = 9.1%; Table 3).

The error analyses generated with MAK-Adv approach determined that the main source of error was the limitations in the approach and not by the quality of the input data provided by remote sensing and forecasting tools. The quantity of the errors were associated to some meteorological variables as temperature, solar radiation or relative humidity, revealing that MAK-Adv approach had a better performance for summertime, with higher uncertainty for ET_o assessment during autumn and winter.

After at least a regional calibration and validation process, and thanks to the integration of remote sensing techniques and forecast tools, the proposed methodology is able to provide accurate ET_o maps for Europe, Africa and part of South America with a spatial resolution of 9 km^2. Although the new approach had similar performance than PM-FAO56 at point scale, the high value of the new approach is the ET_o assessment spatially distributed at regional scale with similar performance than the ET_o assessment determined by a well-managed weather station. The application to the region of Andalusia (Southern Spain) has demonstrated the utility of MAK-Adv approach, able to provide accurate ET_o values for vast areas without requiring a dense weather station network, avoiding the high costs associated to installation and maintaining of this type of networks. Thus, for the analyzed region ET_o values for the totality of the territory were determined, detecting the high spatial variability in ET_o (ET_o ranged between 1029 mm and 1381 mm), impossible to detect with weather station networks.

Agricultural and hydrological studies could use this methodology improving the water management at different spatial scales, providing accurate irrigation scheduling or determining the components of the water balance such as superficial runoff or groundwater recharge.

Acknowledgements

This paper was supported by the grants P10-EXC10-0036/AGR-6126 and PR.AVA.AVA201301.10 of the Regional Government of Andalusia, RTA2011-00015-00-00 of the National Institute for Agricultural and Food Research and Technology (INIA) and by the EUMETSAT within the framework of the LSA SAF. Contributions of Dr. de Bruin and Dr. Trigo are highly appreciated.

References

Allen, R.G., Fisher, D.F., 1990. Low cost electronic weighing lysimeters. Trans. ASAE 33 (6), 1823–1833.

Allen, R.G., Pruitt, W.O., Jensen, M.E., 1991. Environmental requirements of lysimeters. In: Proceedings of the ASCE Specialty Conference on Lysimeters for Evapotranspiration and Environmental Measurements, Honolulu, HI.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.

Alves, M.C., Carvalho, L.G., Vianello, R.L., Sediyama, G.C., Oliveira, M.S., Sá Junior, A., 2013. Geostatistical improvements of evapotranspiration spatial information using satellite land surface and weather stations data. Theor. Appl. Climatol. 113, 155–174.

Bailly, J.S., Levavasseur, F., Lagacherie, P., 2011. A spatial stochastic algorithm to reconstruct artificial drainage networks from incomplete networks delineations. Int. J. Appl. Earth Obs. Geoinf. 12, 853–862.

Berengena, J., Gavilán, P., 2005. Reference evapotranspiration estimation in a highly advective semiarid environment. J. Irrig. Drain. Eng. ASCE 131, 147–163.

Bois, B., Pieri, P., Van Leeuwen, C.V., Wald, L., Huard, F., Gaudillere, J.P., Saur, E., 2008. Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. Agric. For. Meteorol. 148, 619–630.

Cammalleri, C., Ciraolo, G., 2013. A simple method to directly retrieve reference evapotranspiration from geostationary satellite images. Int. J. Appl. Earth Obs. Geoinf. 21, 149–158.

Collins, J.M., 2011. Temperature variability over Africa. J. Clim. 24, 3649–3666.

Cristea, N.C., Kampf, S.K., Burges, S.J., 2013. Revised coefficients for Priestley-Taylor and Makkink-Hansen equations for estimating daily reference evapotranspiration. J. Hydrol. Eng. 18 (10), 1289–1300.

Cristobal, J., Anderson, M.C., 2012. Regional scale evaluation of a MSG solar radiation product for evapotranspiration modeling. Hydrol. Earth Syst. Sci. 9, 8905–8939.

Cristobal, J., Anderson, M.C., 2013. Validation of a Meteosat second generation solar radiation dataset over the northeastern Iberian Peninsula. Hydrol. Earth Syst. Sci. 17, 163–175.

De Bruin, H.A.R., 1987. From Penman to Makkink. In: Proceedings and Information No. 39, TNO Committee on Hydrological Research, The Hague, pp. 5–31.

De Bruin, H.A.R., Lablans, W.N., 1998. Reference crop evapotranspiration determined with a modified Makkink equation. Hydrol. Process. 12, 1053–1062.

De Bruin, H.A.R., Trigo, I.F., Jitan, M.A., Temesgen, E.N., van der Tol, C., Gieske, A.S.M., 2010. Reference crop evapotranspiration derived from geo-stationary satellite imagery – a case study for the Fogera flood plain, NW-Ethiopia and the Jordan Valley, Jordan. Hydrol. Earth Syst. Sci. Discuss. 14, 2219–2228.

De Bruin, H.A.R., Trigo, I.F., Lorite, I.J., Cruz-Blanco, M., Gavilán, P., 2012a. Reference crop evapotranspiration obtained from the geostationary satellite MSG (METEOSAT). Geogr. Res. Abstr. 14, EGU 2012–11453.

De Bruin, H.A.R., Trigo, I.F., Gavilán, P., Martínez-Cob, A., González-Dugo, M.P., 2012b. Reference crop evapotranspiration estimated from geostationary satellite imagery. Remote Sensing and Hydrology. Int. Assoc. Hydrol. Sci. 352, 111–114.

De Wit, A.J.W., van Diepen, C.A., 2008. Crop growth modeling and crop yield forecasting using satellite-derived meteorological inputs. Int. J. Appl. Earth Obs. Geoinf. 10, 414–425.

Er-Raki, S., Chehbouni, A., Khabba, S., Simonneaux, V., Jarlan, L., Ouldbba, A., Rodriguez, J.C., Allen, R.G., 2010. Assessment of reference evapotranspiration methods in semi-arid regions: can weather forecast data be used as alternate of ground meteorological parameters? J. Arid Environ. 74, 1587–1596.

Espadafor, M., Lorite, I.J., Gavilán, P., Berengena, J., 2011. An analysis of the tendency of reference evapotranspiration estimates and other climate variables during the last 45 years in Southern Spain. Agric. Water Manage. 98, 1045–1061.

Farahani, H.J., Howell, H.J., Shuttleworth, W.J., Bausch, W.C., 2007. Evapotranspiration: progress in measurements and modeling in agriculture. Trans. ASABE 50 (5), 1627–1638.

Galleguillos, M., Jacob, F., Prevot, L., French, A., Lagacherie, P., 2011. Comparison of two temperature differencing methods to estimate daily evapotranspiration over a Mediterranean vineyard watershed from ASTER data. Remote Sens. Environ. 115, 1326–1340.

Gavilán, P., Lorite, I.J., Tornero, S., Berengena, J., 2006. Regional calibration of Hargreaves equation for estimating reference ET_o in a semiarid environment. Agric. Water Manage. 81, 257–281.

Gavilán, P., Berengena, J., 2007. Accuracy of the Bowen ratio-energy balance method for measuring latent heat flux in a semiarid advective environment. Irrig. Sci. 25, 127–140.

Gavilán, P., Berengena, J., Allen, R.G., 2007. Measuring versus estimating net radiation and soil heat flux: impact on Penman–Monteith reference ET estimates in semiarid regions. Agric. Water Manage. 89, 275–286.

Geiger, B.C., Meurey, D., Lajas, L., Franchistéguy, D., Carrer Roujean, J.L., 2008. Near real-time provision of downwelling shortwave radiation estimates derived from satellite observations. Meteorol. Appl. 15, 411–420.

Ghilain, N., Arboleda, A., Sepulcre-Cantó, G., Batelaan, O., Ardö, J., Gellens-Meulenberghs, F., 2012. Improving evapotranspiration in a land surface model using biophysical variables derived from MSG/SEVIRI satellite. Hydrol. Earth Syst. Sci. 16, 2567–2583.

Jitan, M.A., (Ph.D. Thesis) 2005. Evapotranspiration of major crops in the Jordan Valley using remote sensing techniques compared with estimated field measurement using Eddy-correlation. University of Jordan, Jordan.

Journée, M., Bertrand, C., 2010. Improving the spatio-temporal distribution of surface solar radiation data by merging ground and satellite measurements. Remote Sens. Environ. 114, 2692–2704.

López-Urrea, R., Martín De Santa Olalla, F., Fabeiro, C., Moratalla, A., 2006. Testing evapotranspiration equations using lysimeter observations in a semiarid climate. Agric. Water Manage. 85, 15–26.

Lorite, I.J., Santos, C., Testi, L., Fereres, E., 2012. Design and construction of a large weighing lysimeter in an almond orchard. Span. J. Agric. Res. 10, 238–250.

Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Eng. 11, 277–288.

Malone, R.W., Bonta, J.V., Stewardson, D.J., Nelsen, T., 2000. Error analysis and quality improvement of the Coshocton weighing lysimeters. Trans. ASAE 43, 271–280.

Mantovani, E.C., Villalobos, F.J., Orgaz, F., Fereres, E., 1995. Modelling the effects of sprinkler irrigation uniformity on crop yield. Agric. Water Manage. 27, 243–257.

Meek, D.W., Hatfield, J.L., 1994. Data quality checking for single station meteorological databases. Agric. For. Meteorol. 69, 85–109.

Monteith, J.L.,1965. Evaporation and environment. In: 19th Symposia of the Society for Experimental Biology, vol. 19. University Press, Cambridge, pp. 205–234.

Pereira, A.R., Pruitt, W.O., 2004. Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. Agric. Water Manage. 66, 251–257.

Persson, A., 2011. User Guide to ECMWF Forecast Products. ECMWF, Available at: http://www.ecmwf.int/products/forecasts/guide/user_guide.pdf

Poças, I., Cunha, M., Pereira, L.S., Allen, R.G., 2013. Using remote sensing energy balance and evapotranspiration to characterize montane landscape vegetation with focus on grass and pasture lands. Int. J. Appl. Earth Obs. Geoinf. 21, 159–172.

Ramirez-Villegas, J., Challinor, A., 2012. Assessing relevant climate data for agricultural applications. Agric. For. Meteorol. 161, 26–45.

Roerink, G.J., Bojanowski, J.S., De Wit, A.J.W., Eerens, H., Supit, I., Leo, O., Boogaard, H.L., 2012. Evaluation of MSG-derived global radiation estimates for application in a regional crop model. Agric. For. Meteorol. 160, 36–47.

Santos, C., Lorite, I.J., Tasumi, M., Allen, R.G., Fereres, E., 2010. Performance assessment of an irrigation scheme using indicators determined with remote sensing techniques. Irrig. Sci. 28, 461–477.

Sepulcre-Canto, G., Vogt, J., Arboleda, A., Antofie, T., 2014. Assessment of the EUMETSAT LSA-SAF evapotranspiration product for drought monitoring in Europe. Int. J. Appl. Earth Obs. Geoinf. 30, 190–202.

Shafer, M.A., Fiebrich, C.A., Arndt, D.S., 2000. Quality assurance procedures in the Oklahoma Mesonetwork. J. Atmos. Ocean. Technol. 17, 474–494.

Schmetz, J., Pili, P., Tjemkes, S., Just, D., Kerkman, J., Rota, S., Ratier, A., 2002. An introduction to Meteosat second generation (MSG). Bull. Am. Meteorol. Soc. 83, 977–992.

Stisen, S., Sandholt, I., Norgaard, A., Fensholt, R., Jensen, K.H., 2008. Combining the triangle method with thermal inertia to estimate regional evapotranspiration. Applied to MSG-SEVIRI data in the Senegal River basin. Remote Sens. Environ. 112, 1242–1255.

Temesgen, B., Eching, S., Davidoff, B., Frame, K., 2005. Comparison of some reference evapotranspiration equations for California. J. Irrig. Drain. Eng. 131, 73–84.

Trigo, I.F., Barroso, C., Viterbo, P., Freitas, S.C., Monteiro, I.T., 2010. Estimation of downward long-wave radiation at the surface combining remotely sensed data and NWP data. J. Geophys. Res. 115, D24118.

Trigo, I.F., Dacamara, C.C., Viterbo, P., Roujean, J.L., Olesen, F., Barroso, C., Camacho-de-Coca, F., Carrer, D., Freitas, S.C., García-Haro, J., Geiger, B., Gellens-Meulenberghs, F., Ghilain, N., Meliá, J., Pessanha, L., Siljamo, N., Arboleda, A., 2011. The satellite application facility for land surface analysis. Int. J. Remote Sens. 32, 2725–2744.

Van Kraalingen, D.W.G., Stol, W., 1997. Evapotranspiration modules for crop growth simulation. Quant. Approaches Syst. Anal. 11, 29.

Voogt, M.P., (MSc Thesis TU Delft) 2006. Meteolook, A Physically Based Regional Distribution Model for Measured Meteorological Variables.

Wright, J.L., 1982. New evapotranspiration crop coefficient. Proc. Am. Soc. Civil Eng. J. Irrig. Drain. Div. 108, 57–74.

Xu, C.Y., Chen, D., 2005. Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. Hydrol. Process. 19, 3717–3734.

Yang, J., Li, B., Liu, S., 2000. A large weighing lysimeter for evapotranspiration and soil-water-groundwater exchange studies. Hydrol. Process. 14, 1887–1897.